100 Years of β Decays

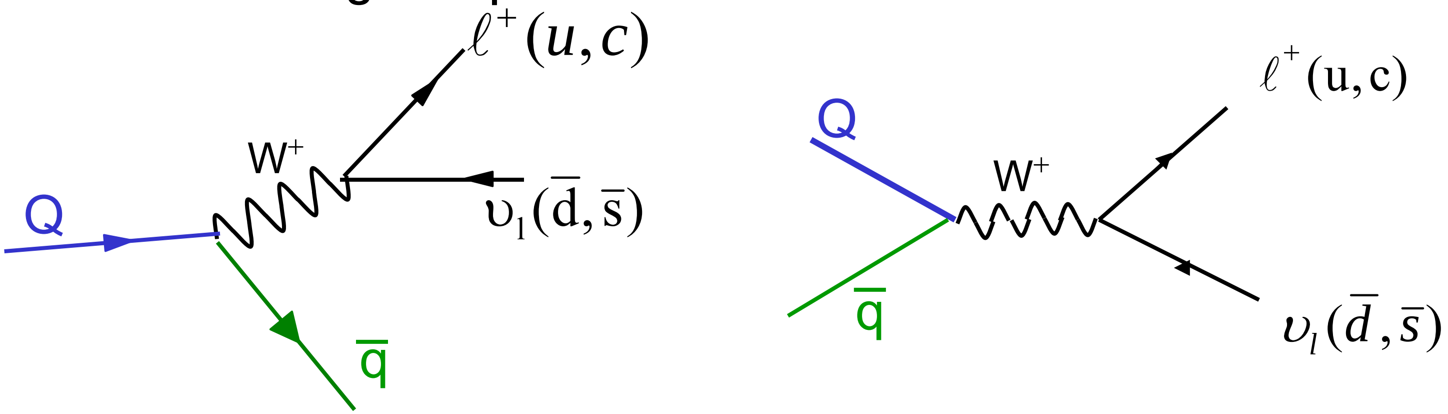
A History of Strong Interactions of Experimenters and Theorists

Vera G. Lüth

SLAC – Stanford University

Role of Semileptonic and Leptonic Decays

- The cleanest signature for a weak decay mediated by the W boson: the emission of a charged lepton and neutrino



- A large variety of such processes, from nuclear β decay to decays of heavy quarks, i.e. covering a range from 15 KeV to 170 GeV
- S.L. decays have allowed us
  - to measure fundamental weak interaction processes, test couplings to charged weak current
  - to test discrete symmetries, and
  - to probe decay dynamics and study strong interactions.

History of Measurements of Nuclear β Decay

- 1907: Three types of radiation were known and it was assumed that they all emitted particles of fixed energy:
  - α particles: strong interactions
  - β particles: weak interactions
  - γ particles: e-m interactions

  The3 types were distinguished mostly by their degrees of absorptivity!

- 1927: Definite proof for continuous β spectrum by Chadwick &Ellis, after many years of conflicting interpretations by Lise Meitner

- 1929: Pauli, in his famous letter addressed to "Meine radioaktiven Damen und Herren", postulates the existence of a

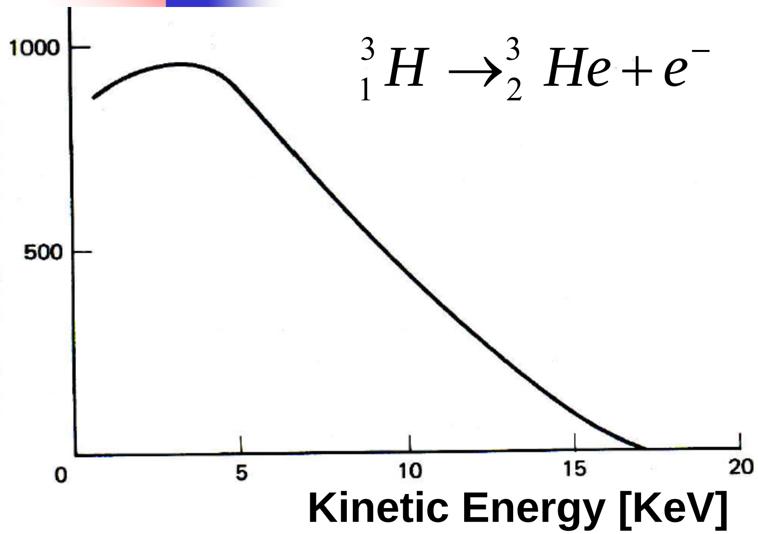
  neutral particle to explain the "energy loss" in β beta decay:

  "It does not appear probable, but only he who dares - wins!"

  1929: Bohr postulates energy non-conservation!

- 1933: Barely a year after the discovery of the neutron by Chadwick, Fermi formulates the theory of β decay

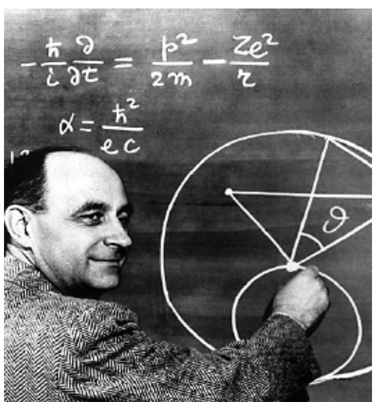
Understanding β Decay



W. Pauli

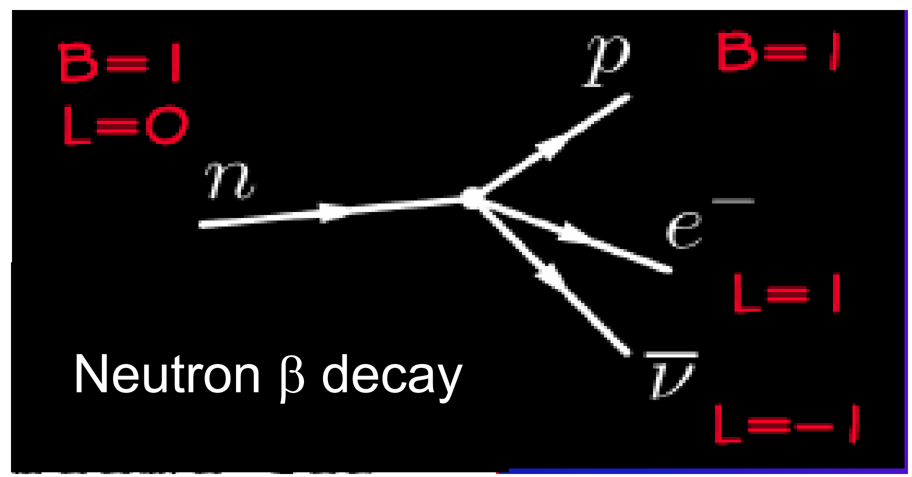
1929: Prediction
"ν" inside nucleus
- *Q=0*
- *s=1/2*
- *m=0, like electron*
- *penetrating*

N.B. The only known particles were p and e- !



E. Fermi

1933: Theory of weak interactions



Critical Role of S.L. Decays

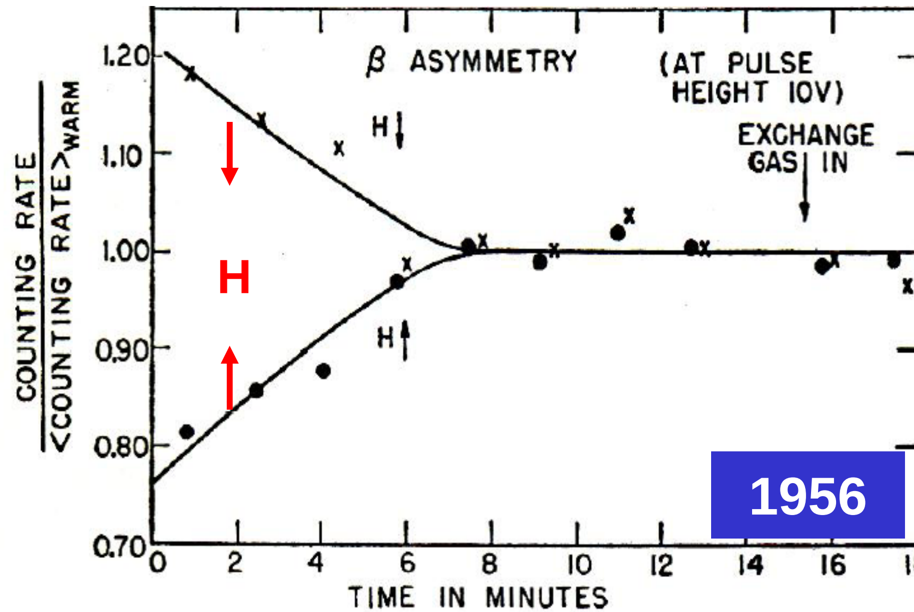
- β decay remained the only known weak process, until the muon, pion and kaon were discovered.
- In the decades to follow, S.L. decays played a critical role in several important discoveries and measurements
  - Parity Violation — Lee, Yang, Wu
  - CP, T Violation and CPT tests in K decays — Lee, Yang, Wolfenstein
  - Electro-weak coupling of Heavy Flavor Quarks: Kobayashi, Maskawa
  - Discovery of $t\bar{t}$ production at Tevatron: $t \rightarrow b\, W^{+} \rightarrow b + \ell^{+}$
  - Direct measurements of neutrino masses
- In the Future
  - Search for New Phenomena at the energy frontier: Tevatron and LHC

Role of β Decay in Discovery of Parity Violation

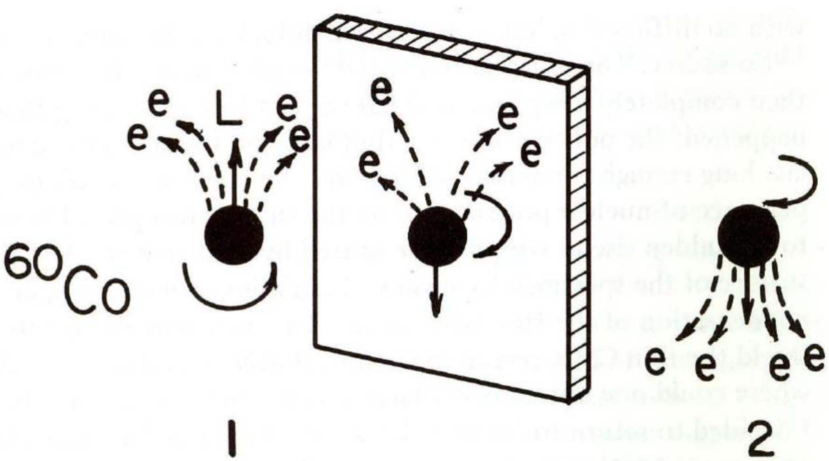
C.S.Wu

E. Ambler

In 1953, Lee, Yang instigated (θ–τ puzzle) searches for parity non-conservation, they suggested this experiment!



$$Co_{27}^{60} \rightarrow Ni_{28}^{60} + e^{-}\overline{\nu}$$



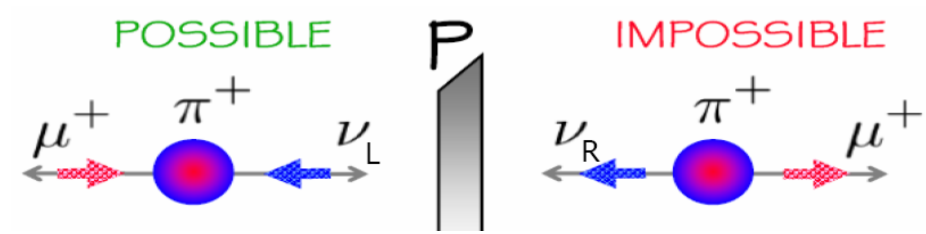
Manifestation of parity violation: The electron direction is correlated with the polarization!

Role of β Decay in Discovery of Parity Violation

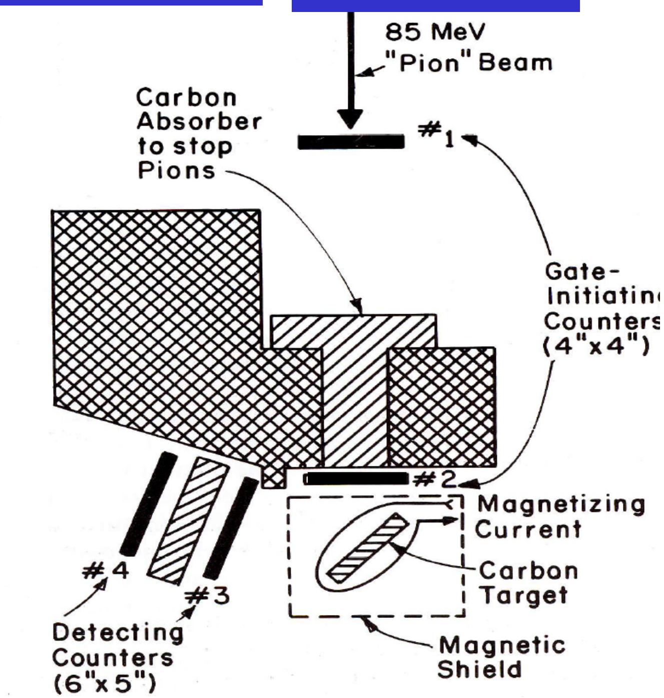
L. Lederman

R.Garvin

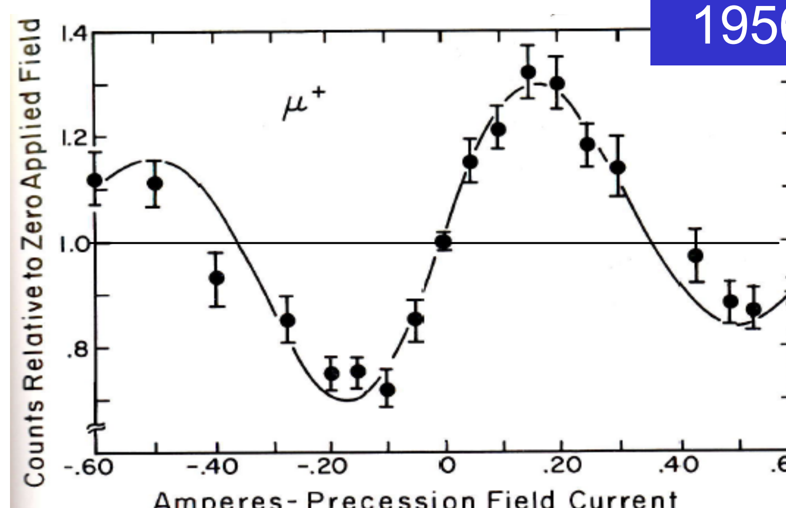
$$\pi^+ \rightarrow \mu^+ \nu, \quad \mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$



Parity violation: Large asymmetry in e- implies polarization of μ+



1956/57



CP Violation in $K^0 \rightarrow \pi^- e^+ \nu$ Decays

- Charge Asymmetry

  $\Gamma(K^0_L \rightarrow \pi^- e^+ \nu) > \Gamma(K^0_L \rightarrow \pi^+ e^- \nu)$

- Mixture of CP eigenstates:

$$|K_L\rangle = \frac{1}{\sqrt{2}}\left\{|K^0\rangle - \varepsilon|\overline{K}^0\rangle\right\}$$

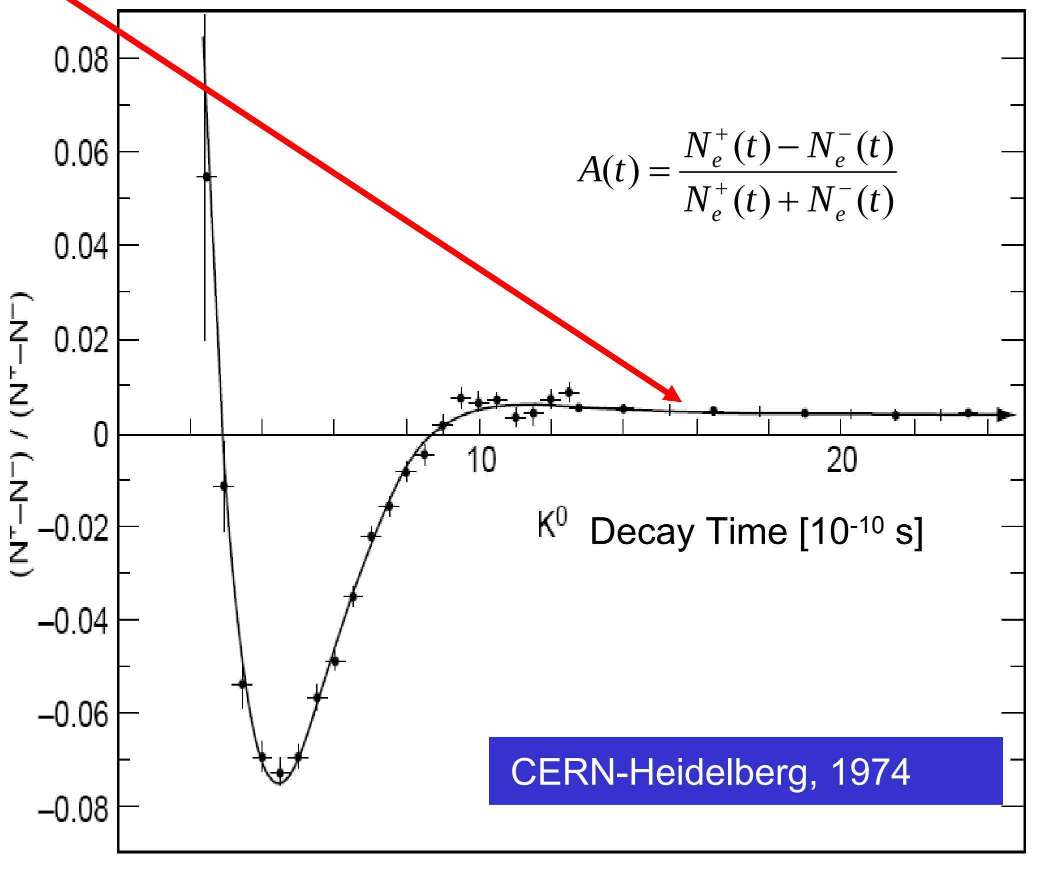
- Current best measurement:

KTeV 2002

$$A_L = 2\,\mathrm{Re}\,\varepsilon = 3.322 \pm 0.074 \times 10^{-3}$$

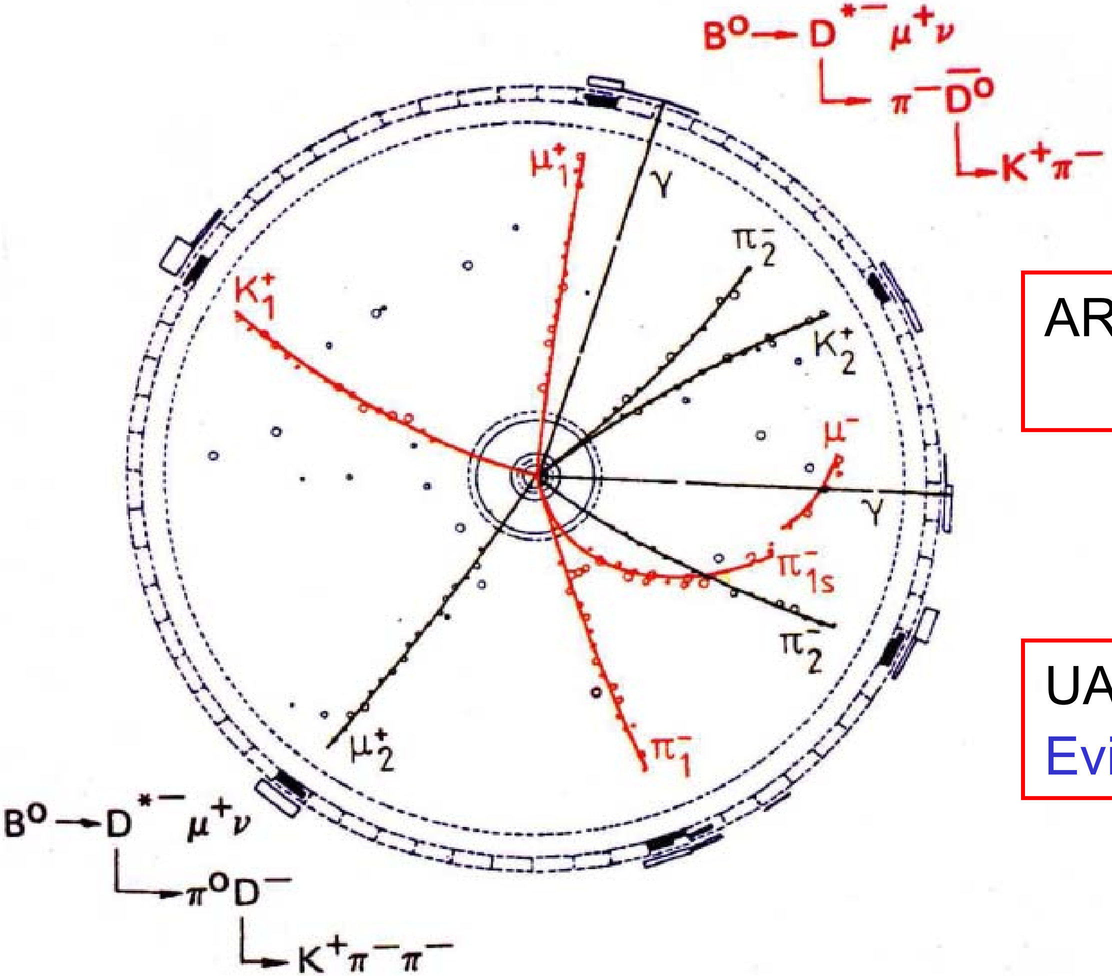
$$\Delta m = 0.5292 \pm 0.0009\ 10^{-10}\mathrm{s}^{-1} = 3.482 \pm 0.006\ 10^{-6}\ \mathrm{eV}$$

$$A(t) \propto 2\,\mathrm{Re}\,\varepsilon + \alpha\, e^{-\Delta\Gamma t/2} \cos \Delta m t$$



Discovery of Mixing in e+e- → B^0 B^0

ARGUS 1987



ARGUS: Signature: 2 D*-
2 μ+ 2 K+

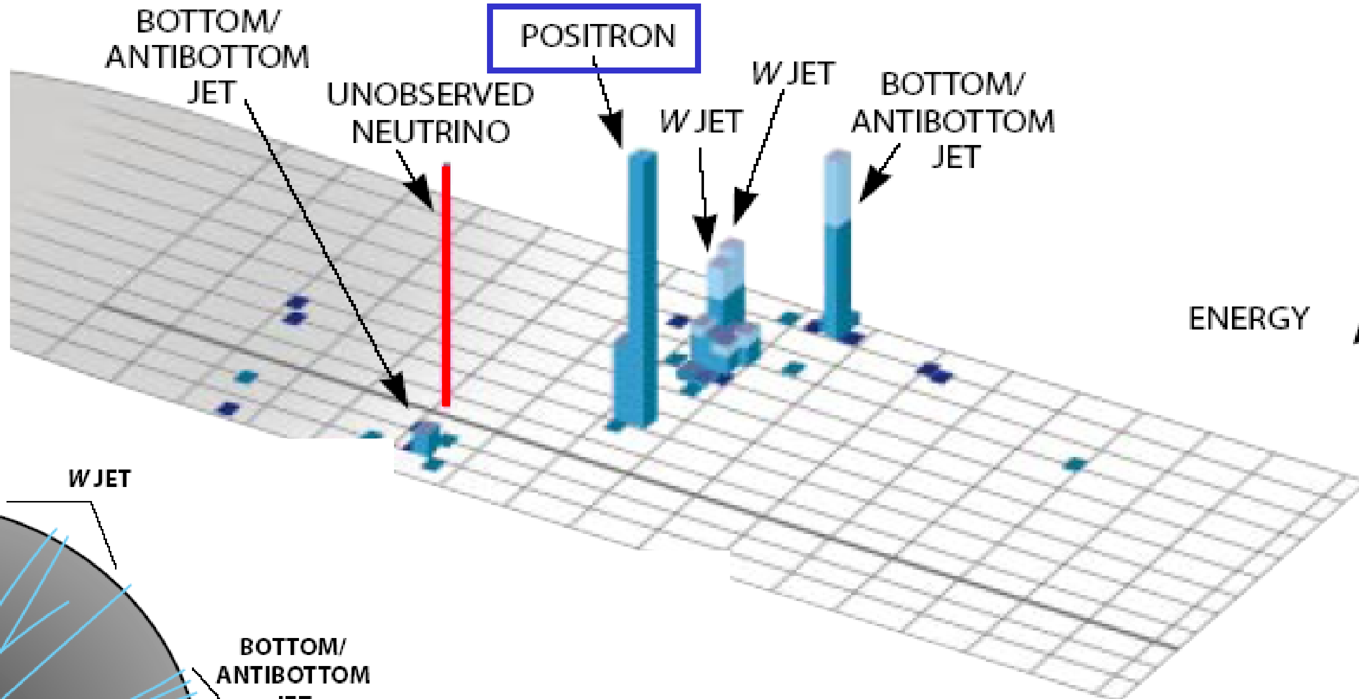
Phys. Lett. 192B (1987) 245.

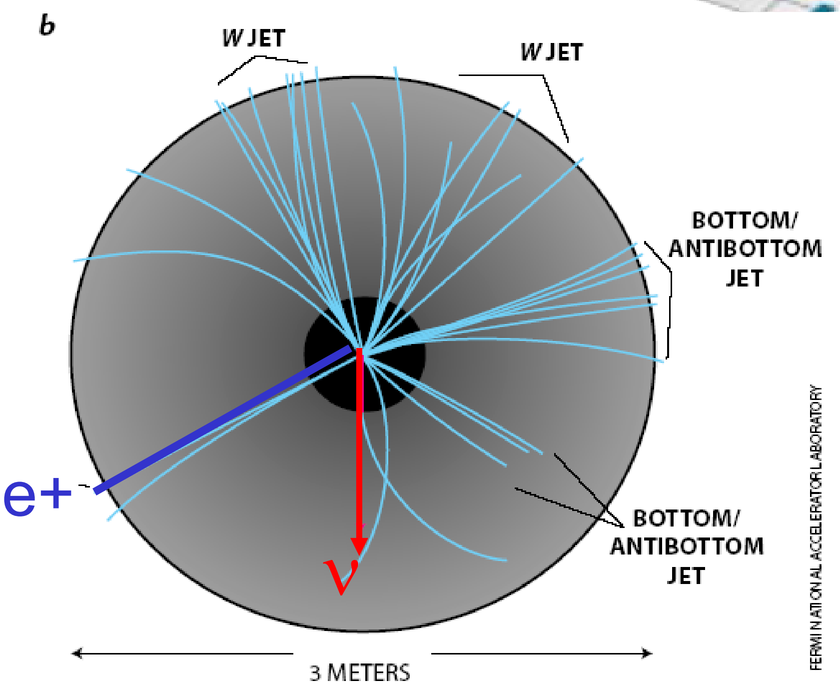
UA1 at SPSC: like-sign di-muons:
Evidence for Bs mixing???

Phys. Lett. 186B (1986) 247.

Discovery of t Quark at Tevatron: 1994

CDF 1994





$\bar{p}p \to \bar{t}\, t + x$

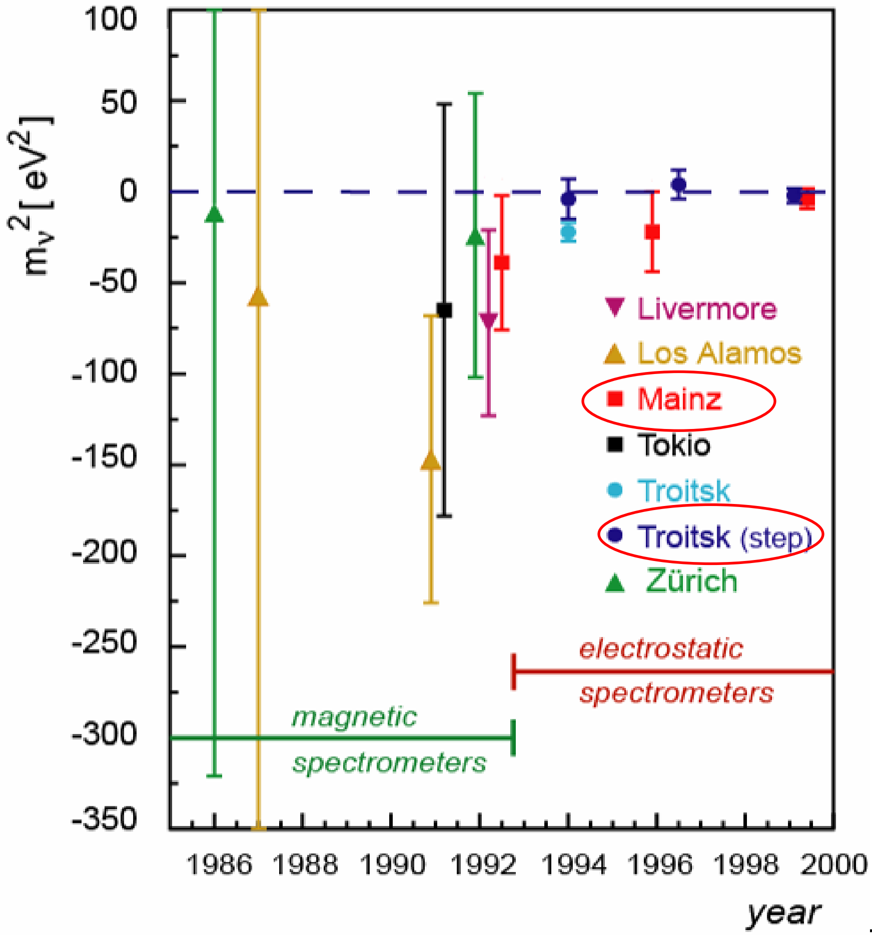
$t \to b\, W^{+} \to e^{+}\nu + jet$

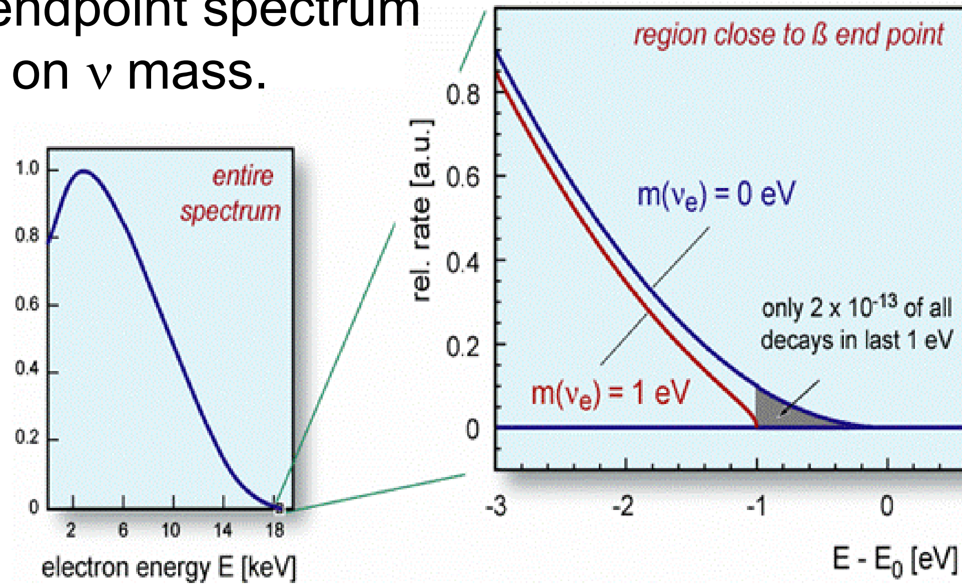
$\bar{t} \to \bar{b}\, W^{-} \to 3\ jets$

Direct Neutrino Mass Measurements

$$^3_1H \rightarrow ^3_2 He + e^-$$

High precision measurements of the endpoint spectrum in ^{3}H β decays performed to set limits on ν mass.





$$m^2(\nu_e) = \sum_j |U_{ej}|^2 m^2(\nu_j)$$

$M(\nu_e) < 2.2$ eV @ 95% CL

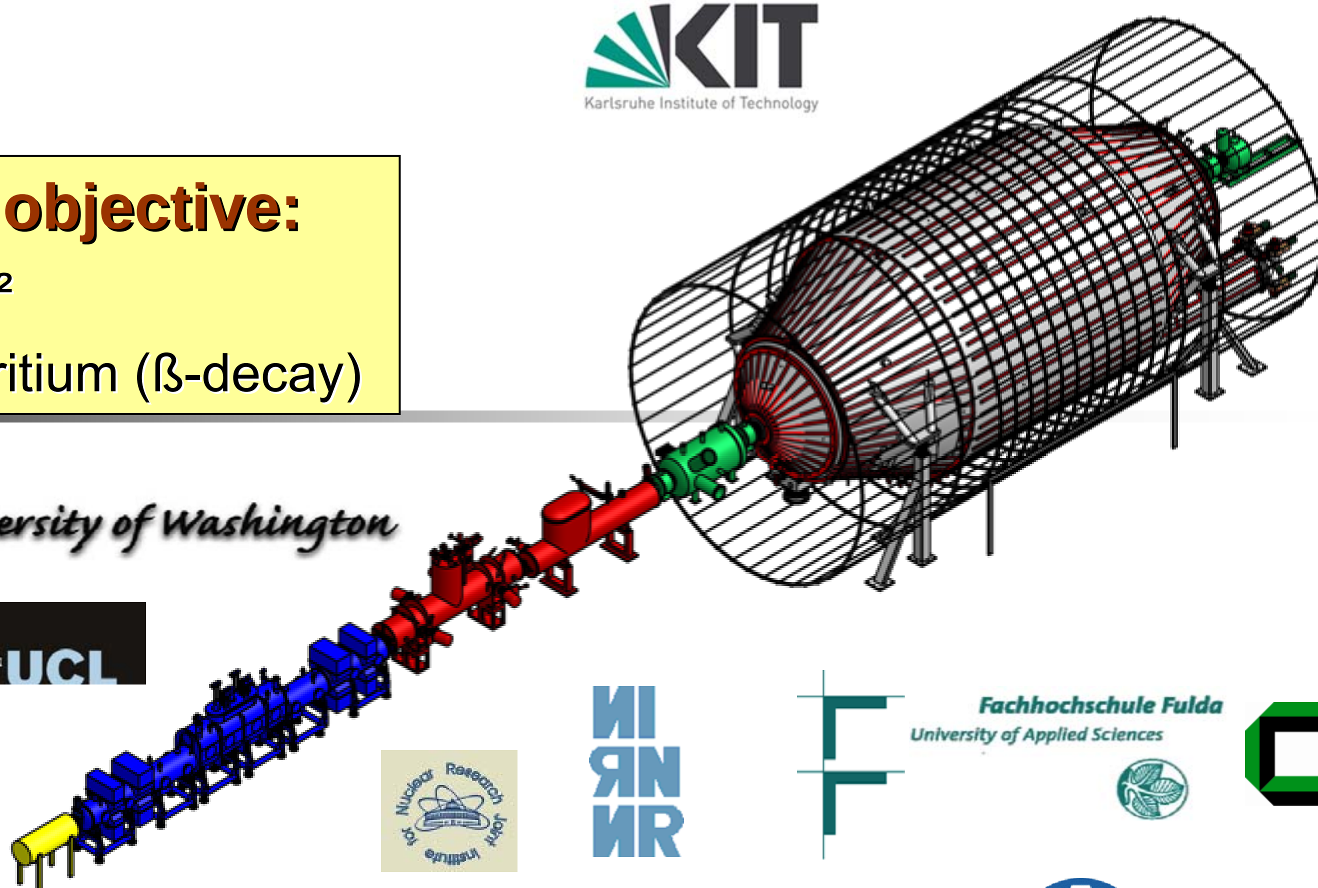
Mainz, EPJ C40, 447, 2005

$M(\nu_e) < 2.05$ eV @ 95% CL

Troitsk, NP A719, ,153, 2003

KATRIN Experiment : First Data 2011

Experimental objective:
- sensitivity: 0.2 eV/c²
- source: Gaseous Tritium (ß-decay)



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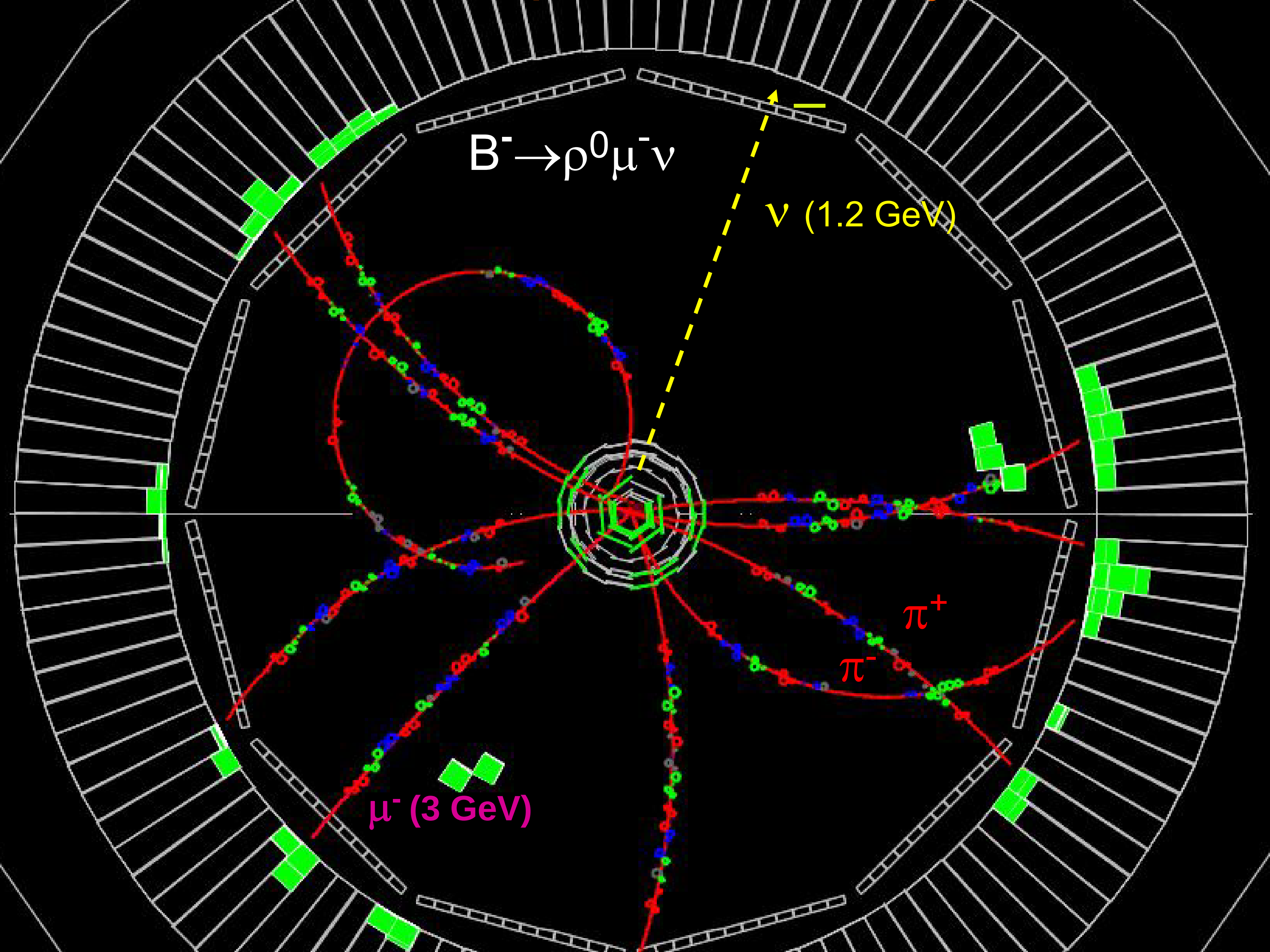
AKADEMIE VĚD ČESKÉ REPUBLIKY

ASTeC

The KATRIN Neutrino Mass Spectrometer

Diameter:	10 m
length:	23 m
weight:	200 t
pressure:	10^{-14} bar

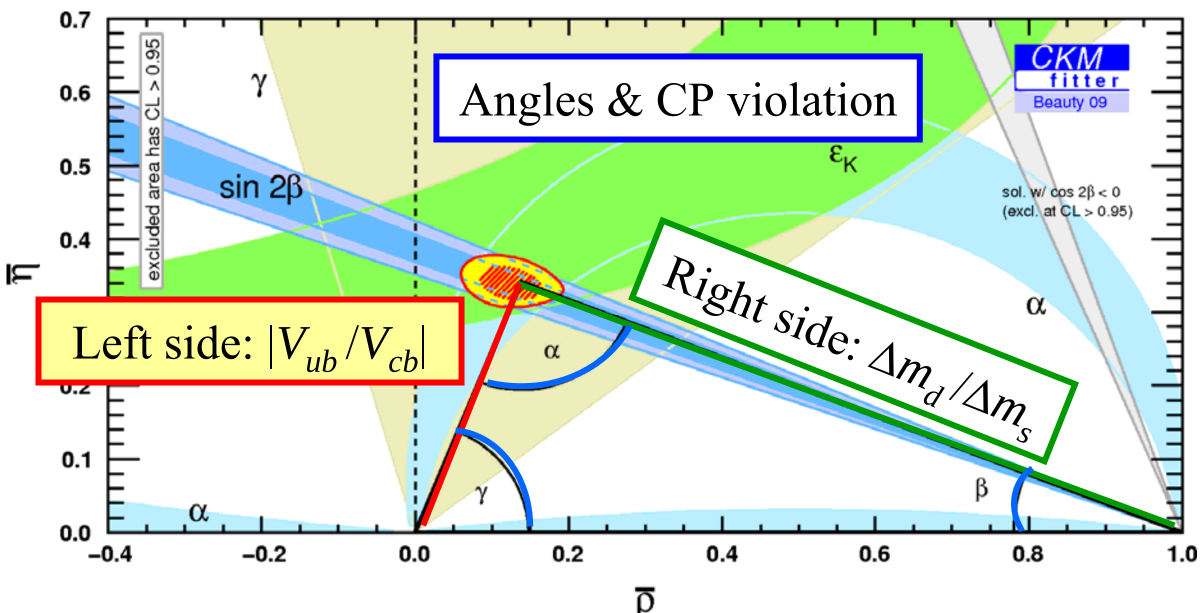


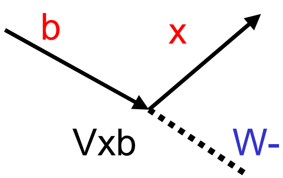
$B^- \rightarrow \rho^0 \mu^- \nu$
ν (1.2 GeV)
π^+
π^-
μ^- (3 GeV)

Semileptonic B Decays – Why do we care?

- SM framework for CP Violation – CKM Matrix
  - S.L. decays are $\Delta B=1$ tree level processes - largely insensitive to NP
  - CP Violation via loop $\Delta B=2$ processes – some potentially impacted new NP
  - Consistency with CKM framework – OK

    but this does not really explain of the cause of CP Violation





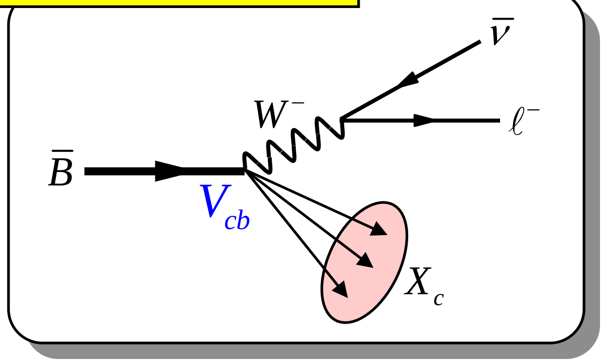
- $|V_{ub}|/V_{cb}|$ determines side opposite β
- $|V_{cb}|^4$ enters ε_K constraint
- Higher precision and redundancy are needed!

Analyses of Inclusive and Exclusive S.L. Decays

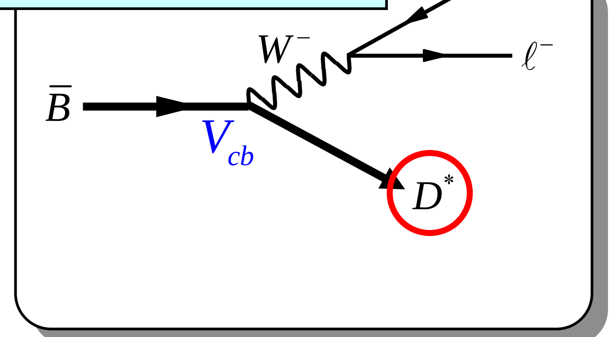
- Exclusive: Detect both specific hadrons and leptons
- Inclusive: Detect only leptons, sum over all final state hadrons

Events may be tagged by reconstructed 2nd B meson in event

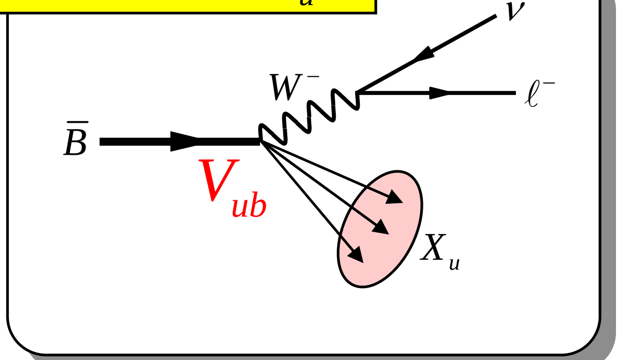
Inclusive $B \to X_c \ell \nu$



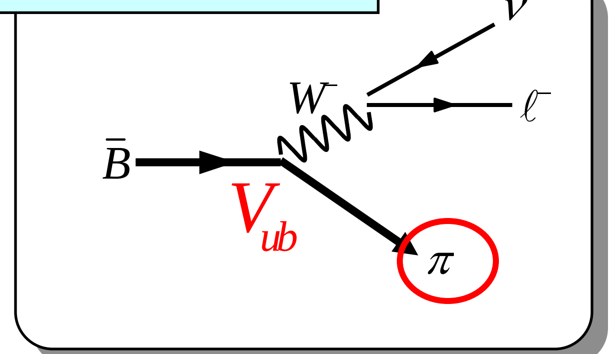
Exclusive $B \to D^* \ell \nu$

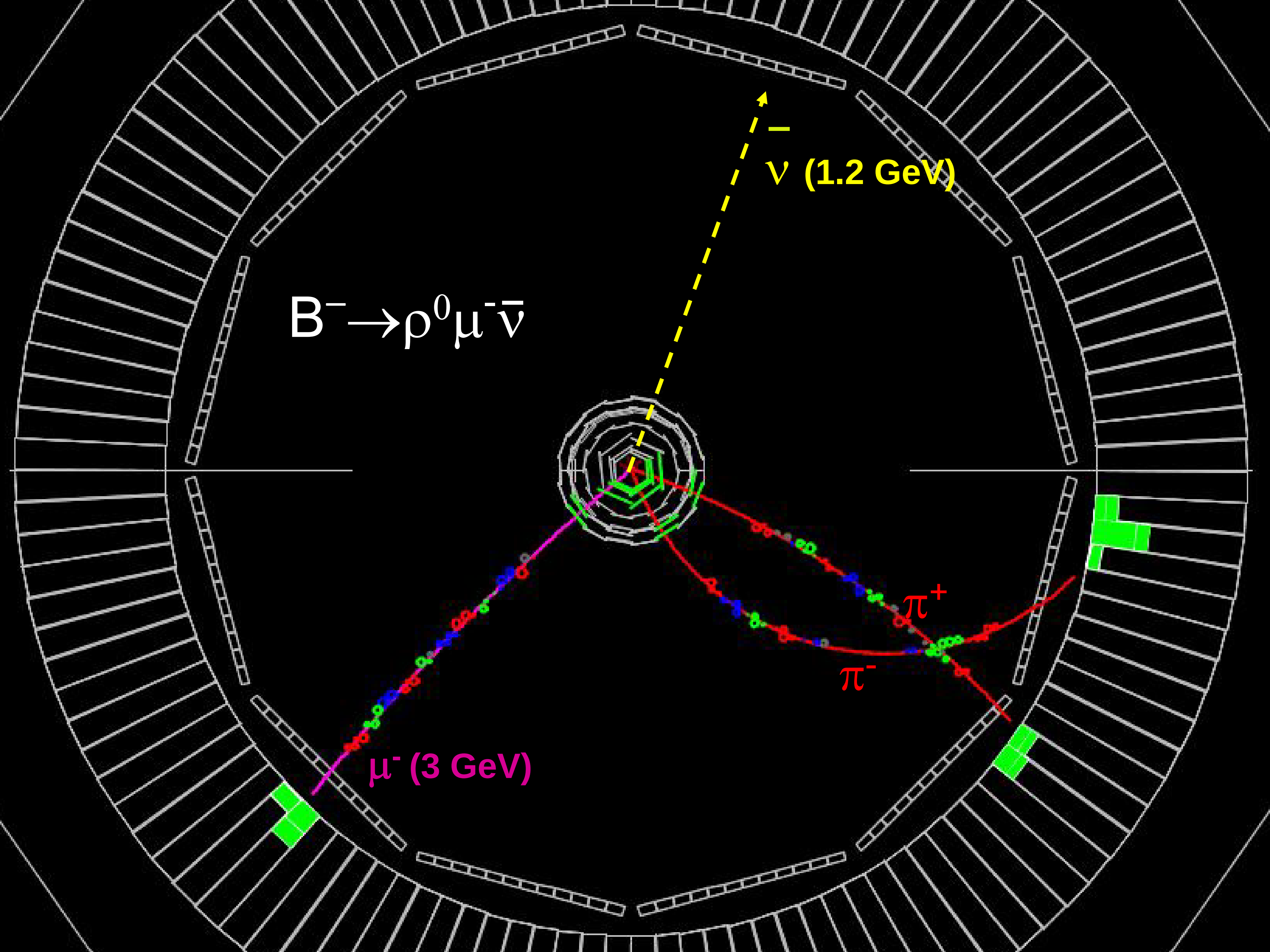


Inclusive $B \to X_u \ell \nu$



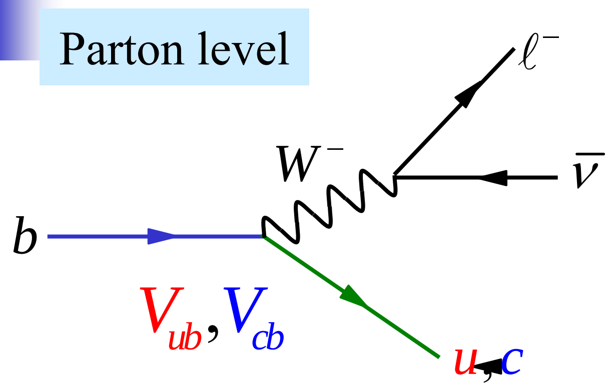
Exclusive $B \to \pi \ell \nu$

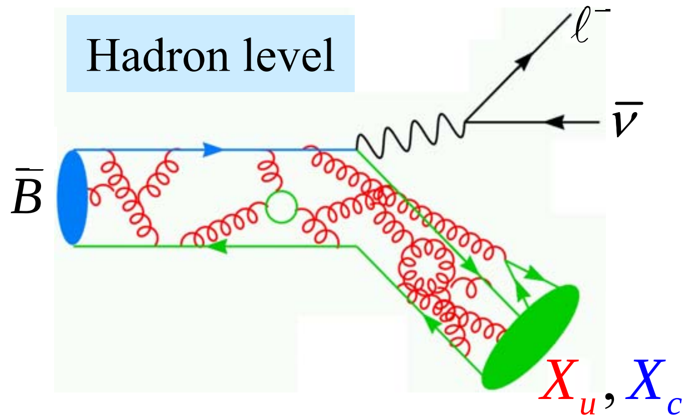




ν̄ (1.2 GeV)
$B^- \to \rho^0 \mu^- \bar{\nu}$
π^+
π^-
μ^- (3 GeV)

Semileptonic B Decays – Probe for $|V_{cb}|$ and $|V_{ub}|$





- Rate depends on CKM elements $|V_{cb}|$ or $|V_{ub}|$, and quark masses m_b (and m_c)
- The leptonic current factors out cleanly

$$\Gamma_{Sl} \propto G_F^2 m_b^5 |V_{xb}|^2 |L_\mu|^2 \left|\langle X|J_L^\mu|B\rangle\right|^2$$

- Hadronic terms must be understood:
  - Exclusive decays: Form factors $F_i(q^2)$,
    - FF Shape from data, Normalization $F_i(w=1)$, from Theory: LQCD, LCSR
  - Inclusive decays: OPE in powers $1/m_b$ and α_s
    - HQE from QCD: perturbative and non-perturbative
    - quark masses and universal non-perturbative parameters enter,
    need to be extracted from data: $B \to X\ell\nu$ and $B \to X s\gamma$ and other

$|V_{cb}|$ from Inclusive $B \to X_c \ell \nu$ and $B \to X_s \gamma$ Decays

Based on OPE, total decay rate inclusive $B \to X_c \ell \nu$

$$\Gamma_{SL} = |V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3}(1 + A_{EW})A_{pert} \times [c_0(r) + \frac{0}{m_b} + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}) + \ldots]$$

free quark decay

perturbative corrections

Non-perturbative power corrections

μ_π^2 ~ kinetic energy of b-quark in B

μ_G^2 ~ chromomagnetic moment (B-B* mass splitting)

- Similar expressions for $B \to X_u \ell \nu$ and $B \to X_s \gamma$
- For comparison with data, study moments of inclusive distributions over large ranges of phase space to avoid problem with quark-hadron duality
- Moments can be calculated as a function of cuts on E_ℓ or E_γ:

$$\langle M_x^n \rangle|_{E_\ell > E_0} = \tau_B \int_{E_0} M_x^n d\Gamma = f(E_0, m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)$$

Cut-off

quark masses

Non-perturbative parameters

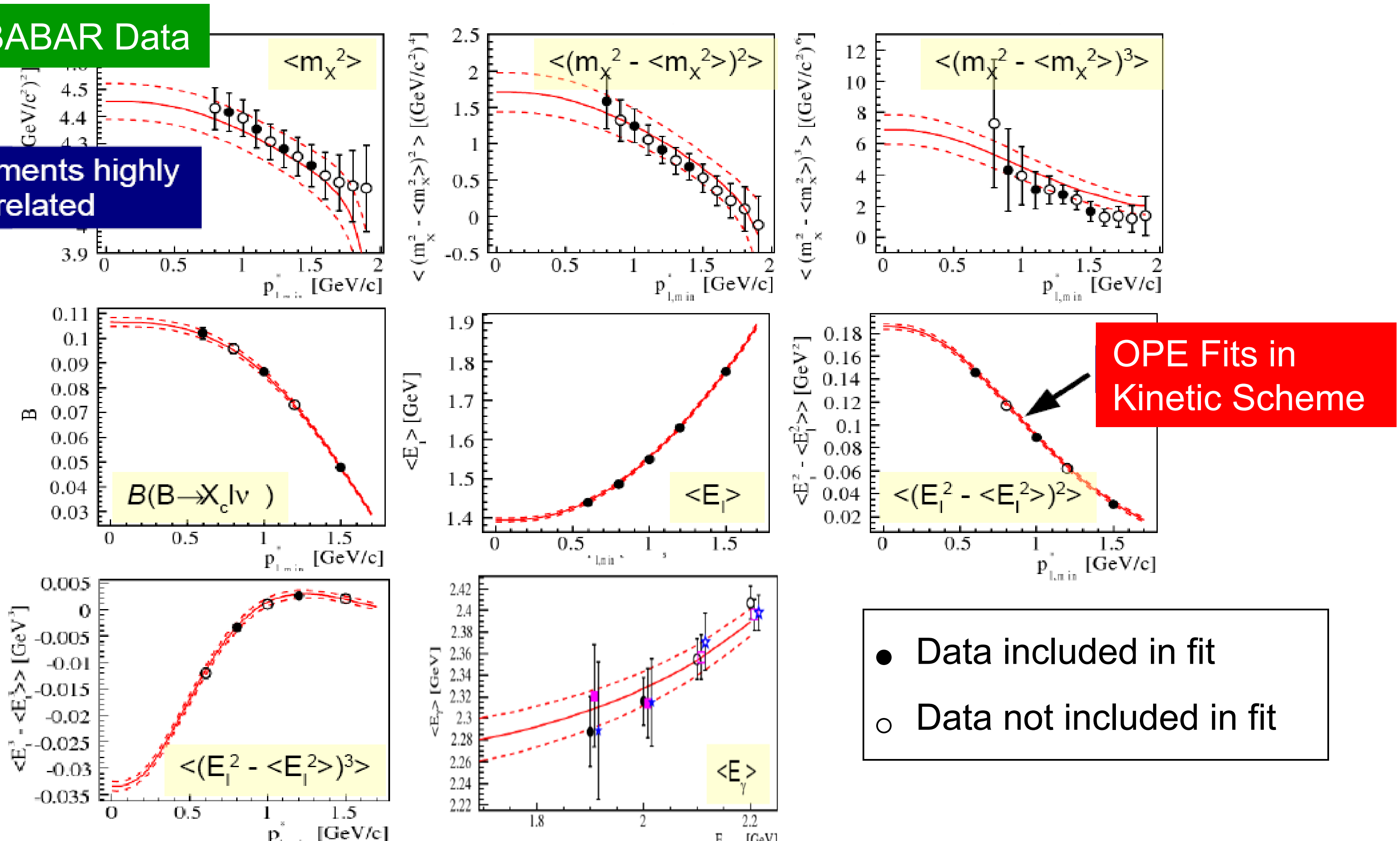
- Calculations available in "kinetic" and "1S" mass schemes

  Benson, Bigi, Gambino, Mannel, Uraltsev   Bauer, Ligeti, Luke, Manohar, Trott,

- >60 measured moments available form DELPHI, CLEO, BABAR, Belle, CDF

Global Fit to Moments in $B \to X_c \ell \nu$ and $B \to X_s \gamma$ Decays

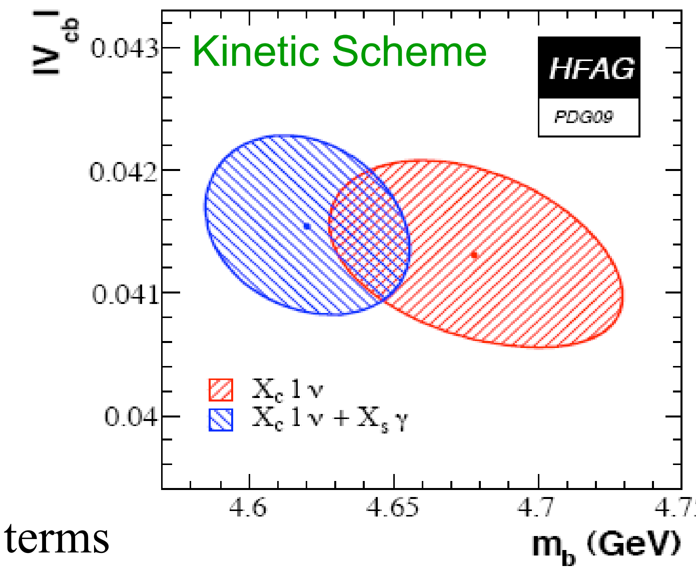
E_ℓ	lepton energy spectrum	E_γ	photon energy spectrum
B	Branching fraction	m_X^2	hadron mass sq. spectrum



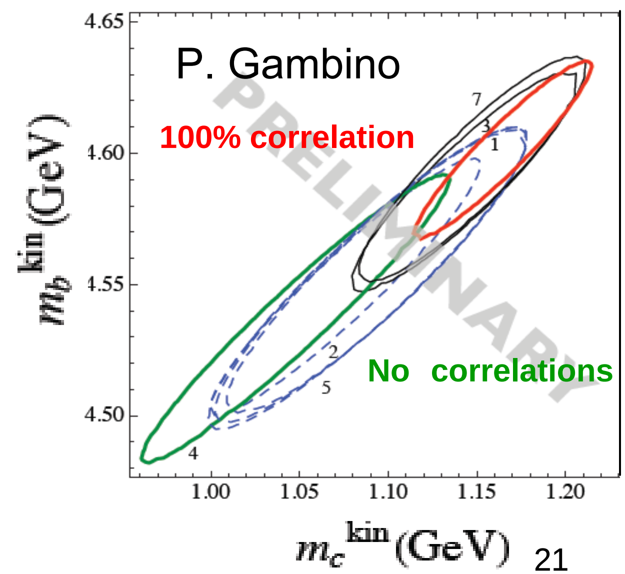
$|V_{cb}|$ from Global OPE Fits to Moments

- HFAG Result of Global Fit to 64 moments

$$|V_{cb}| = (41.31 \times 10^{-3} (1 \pm 1.2\%_{fit} \pm 1.4\%_{theory})$$
$$m_b = 4.678 \pm 0.051 \text{ GeV}$$
$$m_b - m_c = 3.427 \pm 0.021 \text{ GeV}$$
$$\mu_\pi^2 = 0.428 \pm 0.044 \text{ GeV}^2$$



- Status and Issues
  - Major effort underway to improve higher order QCD terms
    - $\alpha_s^2 \mu_\pi^2$: likely to impact m_b
    - $\alpha_s^2 \beta_0$: mostly impacts total rate and thus $|V_{cb}|$
    - m_b^4 : terms expected to be small
  - Local OPE for $B \rightarrow X_s\gamma$ on less solid ground, especially with cut $E_\gamma > 1.8$ GeV (Neubert LP07)
  - unavoidable correlations among moments treatment somewhat ad hoc! impact quark masses
  - Results on m_b are crucial input to $|V_{cb}|$ extraction



Global Fit to Moments: b-quark mass

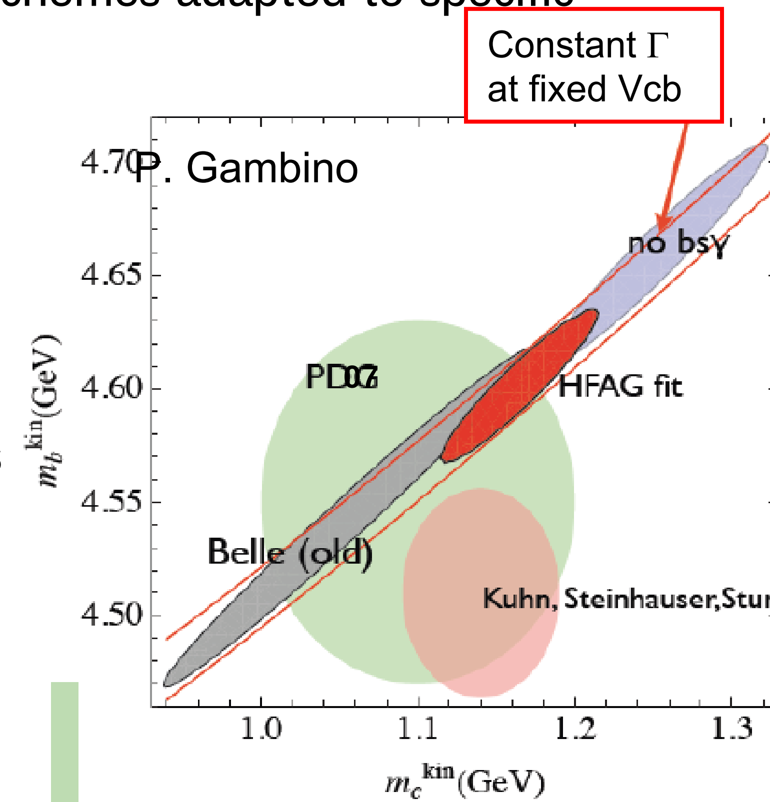
- Fits would greatly benefit from additional external input, primarily m_b and m_c
- In kinetic scheme $\Gamma \sim m_b^2(m_b-m_c)^3$,

  fits to moments show linear relation between m_b and m_c!
- Confinement - Quark masses are not physical observables, but defined as formal parameters in QCD action – choice of schemes adapted to specific processes
- Recent update of sum rule calculations at NNNLO in $\overline{\text{MS}}$ scheme

  $m_b(m_b) = 4.163 \pm 0.016$ GeV !!

  $m_c(m_c) = 1.279 \pm 0.013$ GeV !!

  Chertyrkin et al. arXiv: 0907.2120 (2009)
- Currently, translation to kin. scheme increases error to 40 MeV! Still smaller than current PDG error!
- Goal is to fit masses in $\overline{\text{MS}}$ scheme directly, so conversion error can be avoided!

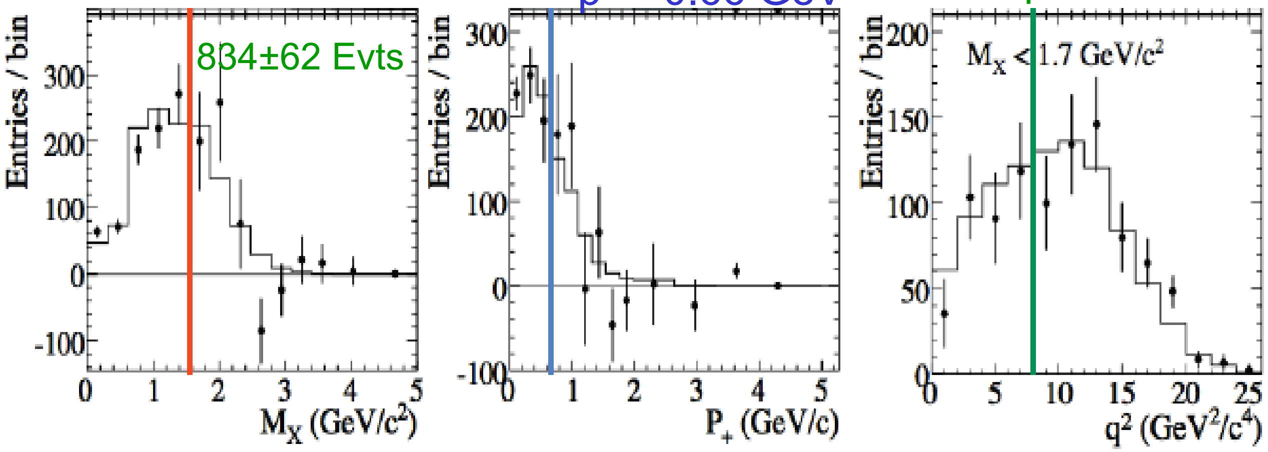


$|V_{ub}|$ from Inclusive $B \rightarrow X_u \ell \nu$

- Experimental challenges
  - Large $B \rightarrow X_c \ell \nu$ background (50x larger) requires restriction in phase space
  - Variables like Mx, P+=Ex-|px|, q^2 require full event reconstruction
  - Tagged events (other B reconstructed) reduce samples to 1 evt/0.5M BB
  - Background BF and Bg and Signal distributions not that well understood
- Theoretical challenges – simplifications of OPE in limited phase space
  - Rates become sensitive to b-quark PDFs in B meson.
    - Unknown higher orders terms in α_s and $1/m_b$ expansions
    - Shape functions (SF) – to be extracted from data
      - Leading order in 1/mb: universal SF
      - Order Λ_{QCD}/m_b: several subleading SF
    - Weak annihilation - process not included - could be ~5%
- Current QDC predictions are for one specific region, require extrapolation
    - BLNP: SCET based Bosch, Lange, Neubert, Paz (2004,2005)
    - GGOU: OPE based Gambino, Giordani, Osola, Uraltsev (2007)
    - BLL: OPE based Bauer, Ligeti, Luke (2001)

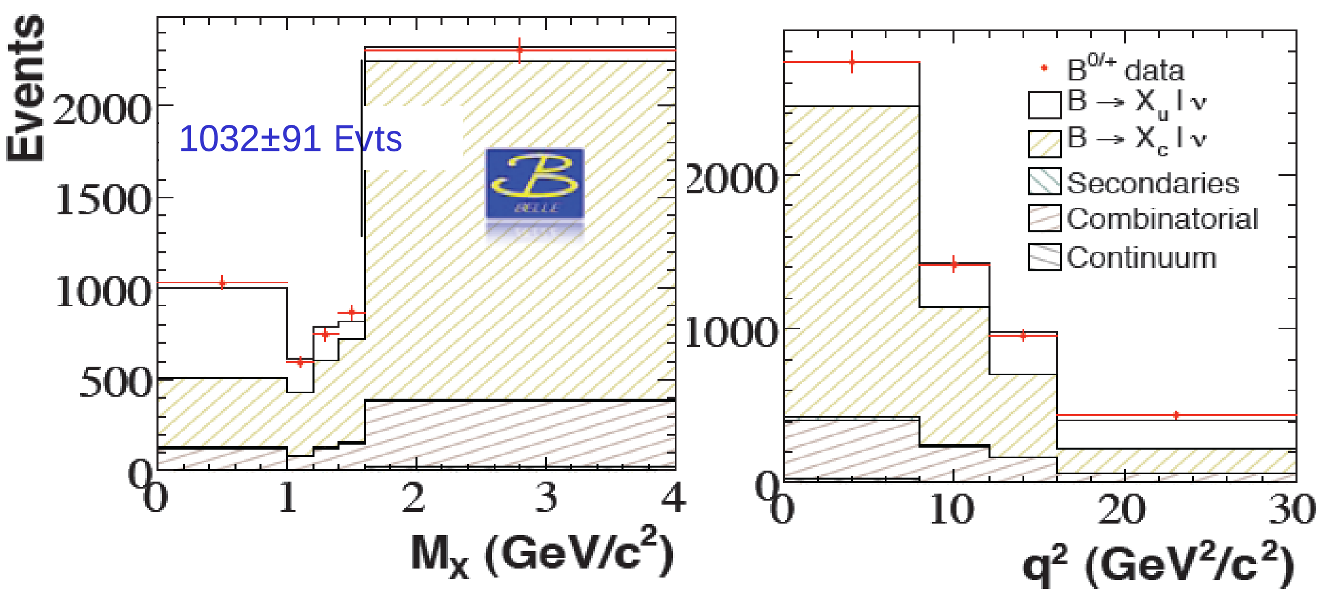
$|V_{ub}|$ from Inclusive $B \rightarrow X_u \ell \nu$

mx <1.55 GeV　　p+ <0.66 GeV　　q^2 >8 GeV2



BABAR 383M BB

Mx<1.55	$\lvert V_{ub}\rvert$ (10^{-3})
BLNP	4.02±0.19±0.29
GGOU	3.98±0.19±0.29
GDE	4.56±0.22±0.32



Belle 660M BB

No Cut	$\lvert V_{ub}\rvert$ (10^{-3})
BLNP	4.37±0.26±0.23
GGOU	4.41±0.26±0.21
GDE	4.46±0.26±0.16

Q: Do we understand the uncertainties?

Current Inclusive $|V_{ub}|$ Measurements

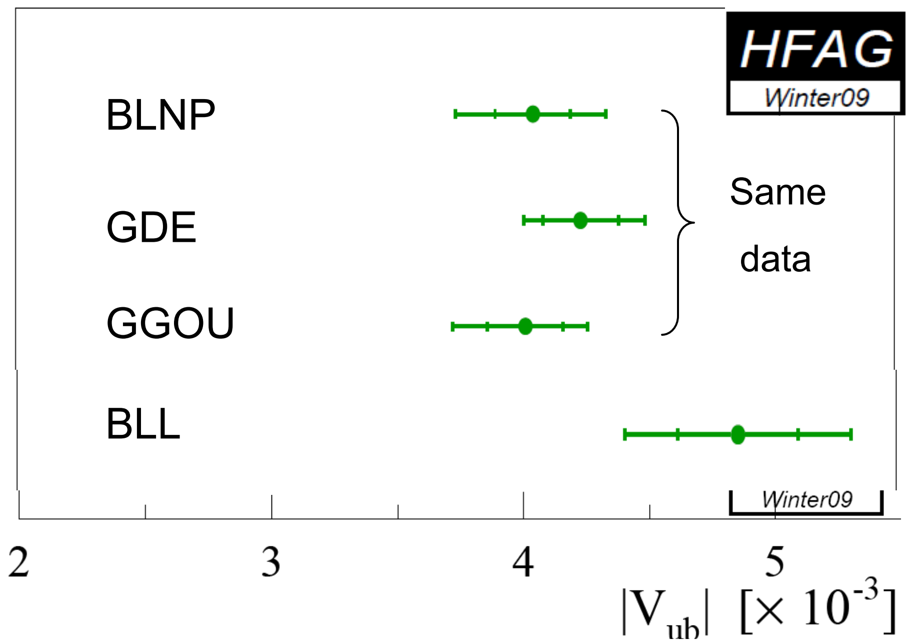
BLNP - HFAG

$|V_{ub}| = (4.06 \pm 0.15_{exp} \pm 0.27) \times 10^{-3}$

Total Error: 7.2 % total

$\pm 2.1_{stat} \pm 2.3_{exp}$ } Exp. 3.6%

$\pm 1.2_{bc\ model} \pm 1.3_{bu\ model}$
$\pm 4.9_{HQ\ param} \pm 0.4_{SF\_form}$
$\pm 0.9_{sub\ SF} \pm 1.5_{scale} \pm 3.4_{WA}$ } Theory 6.2%



- Proposed improvements
  - Factorize SF into non-perturbative (from data) and perturbative (from theory)
  - Develop Global Fit to moments from $B \to X_u l\nu$ and $B \to X_s\gamma$ to extract $|V_{ub}|$, m_b, μ_π^2. Use external input on quark masses
  - Avoid translation between mass schemes
  - Find ways to combine data in different kinematic regions, experiments

Extraction of $|V_{cb}|$ from $B \to D^{(*)} \ell\nu$ Decays

- The differential decay rate

Universal Form Factor

Phase Space

$$\frac{d\Gamma(B\to D^{(*)}\ell\nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 F^2(w,\theta_\ell,\theta_V,\chi)K(w)$$

  - $B \to D\,\ell\nu$: a single FF G(w)
  - $B \to D^*\ell\nu$: $F(w,\theta_\ell,\theta_V,\chi)$ incorporates 3 form factors, $A_1(w)$, $A_2(w)$, $V(w)$
- HQ Symmetry predicts a unique universal F(w) with
  - Common shape given by slope ρ^2, constraints by analyticity and unitarity
  - Normalization at zero-recoil: F(w=1)=G(w=1)=1

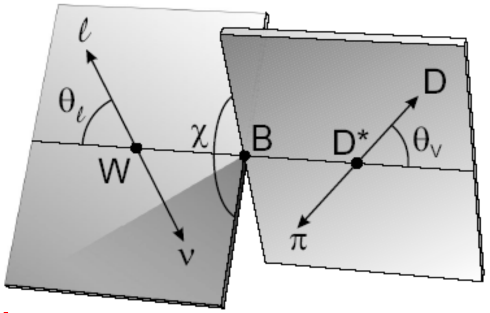
    QCD (and QED) correction to F(1) needed! Lattice QCD
- Extract FF parameters by fits to differential decay rates
  - $B \to D\,\ell\nu$: 1-dim decay distribution $\Gamma(w)$:

    parameters: $|V_{cb}|$ G(1) and slope ρ^2
  - $B \to D^*\,\ell\nu$: 4-dim decay distribution $\Gamma(w,\theta_\ell,\theta_V,\chi)$

    parameters: $|V_{cb}|$ F(1), slope ρ^2, $R_1(w=1)$ and $R_2(w=1)$,

    Fit - either fully 4-dimensional distributions – high sensitivity to R_1 and R_2

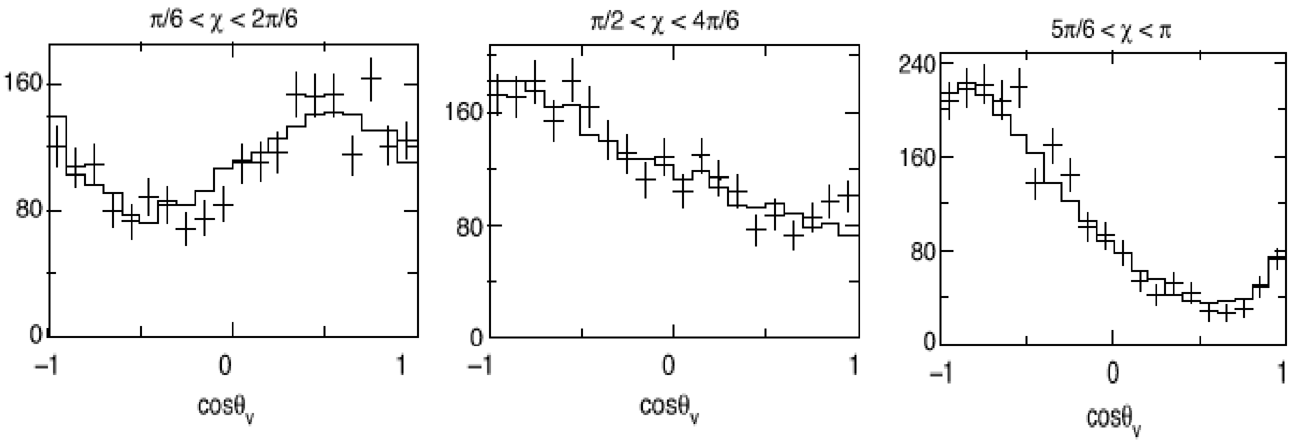
    - or 4 1-dimensional projections



Extraction of $|V_{cb}|$ from $B \to D^* \ell \nu$ Decay Distributions

BABAR
80/fb

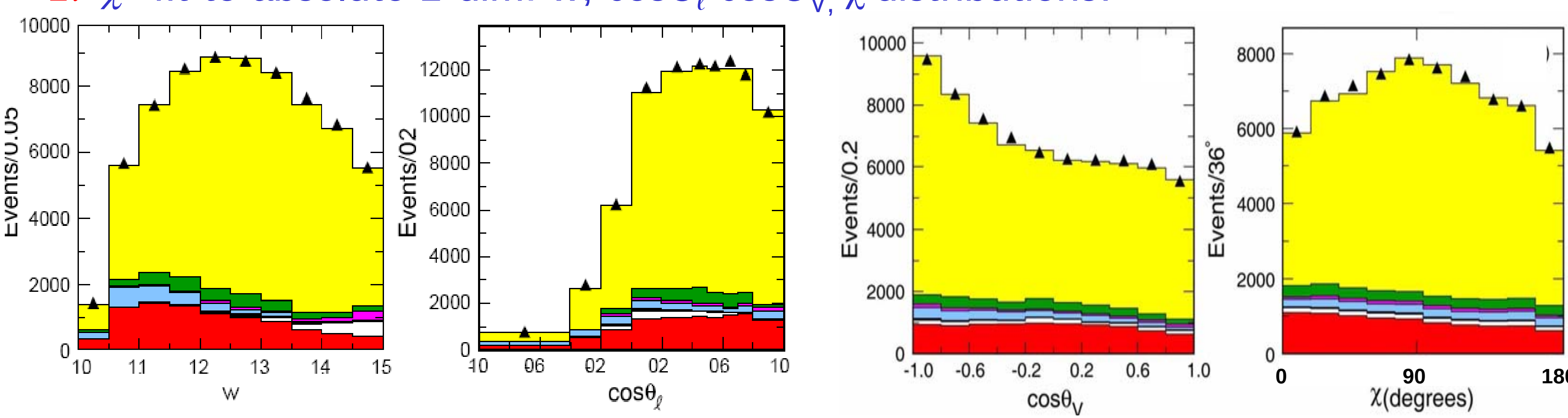
1. Maximum likelihood fit to 4-dim. decay distribution”



Most sensitivity to ρ^2, R_1,R_2 from 4-dim distributions – only BABAR and CLEO

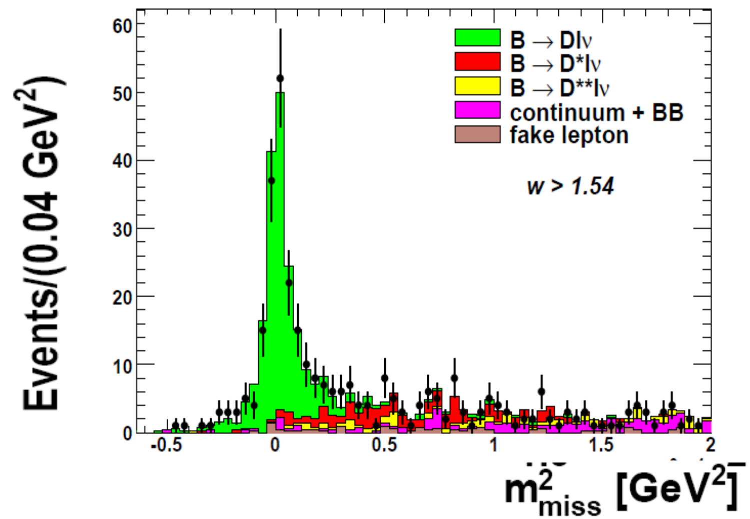
Only small fraction of data analyzed by Belle and BABAR – Embarassment !

2. χ^2 fit to absolute 1-dim. w, $\cos\Theta_\ell$ $\cos\Theta_V$, χ distributions:



Extraction of $|V_{cb}|$ from $B \to D \ell \nu$ Decay Distributions

BABAR, to be published in PRL



- The decay rate (integrated over angles) :

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^2} |V_{cb}|^2 G^2(w) K^2(w)$$

Form factor

Phase space

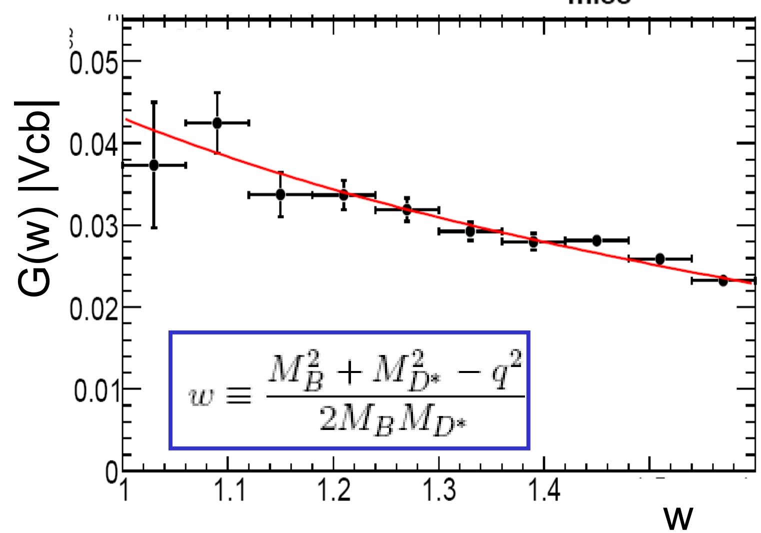
- Simpler, single FF G(w),
- shape is expressed in term of slope parameter slope ρ^2, with analyticity constraints:

$$\frac{G(w)}{G(1)} = 1 - \rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3$$

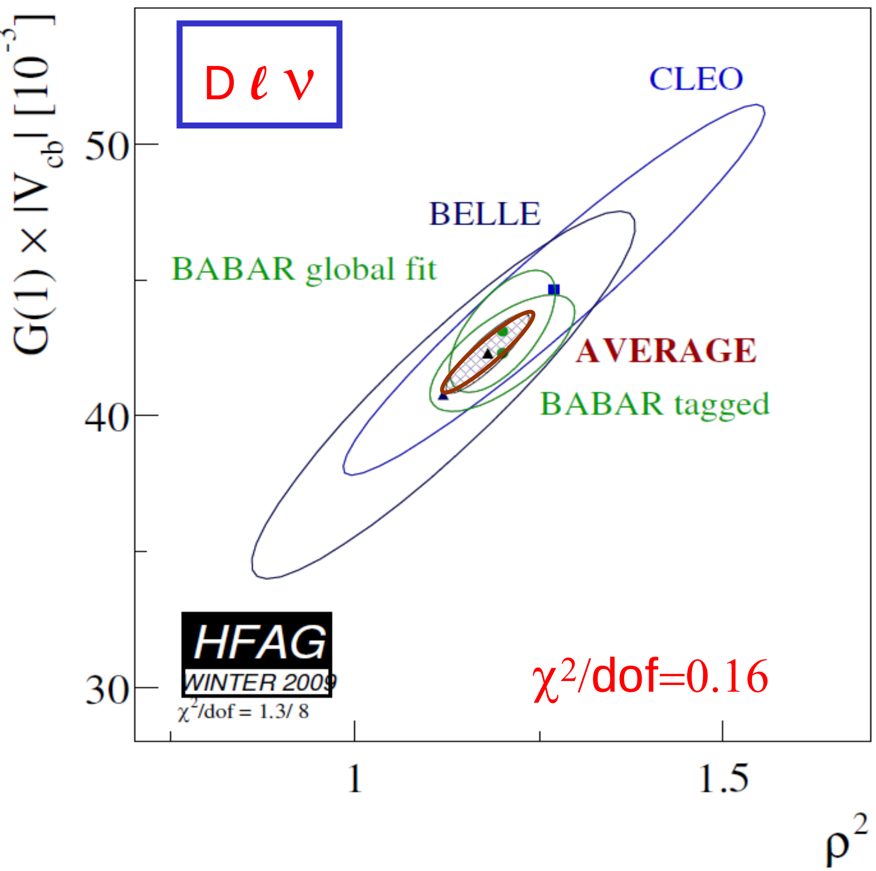
Caprini, Lellough, Neubert, Nucl. Phys. B530, 217

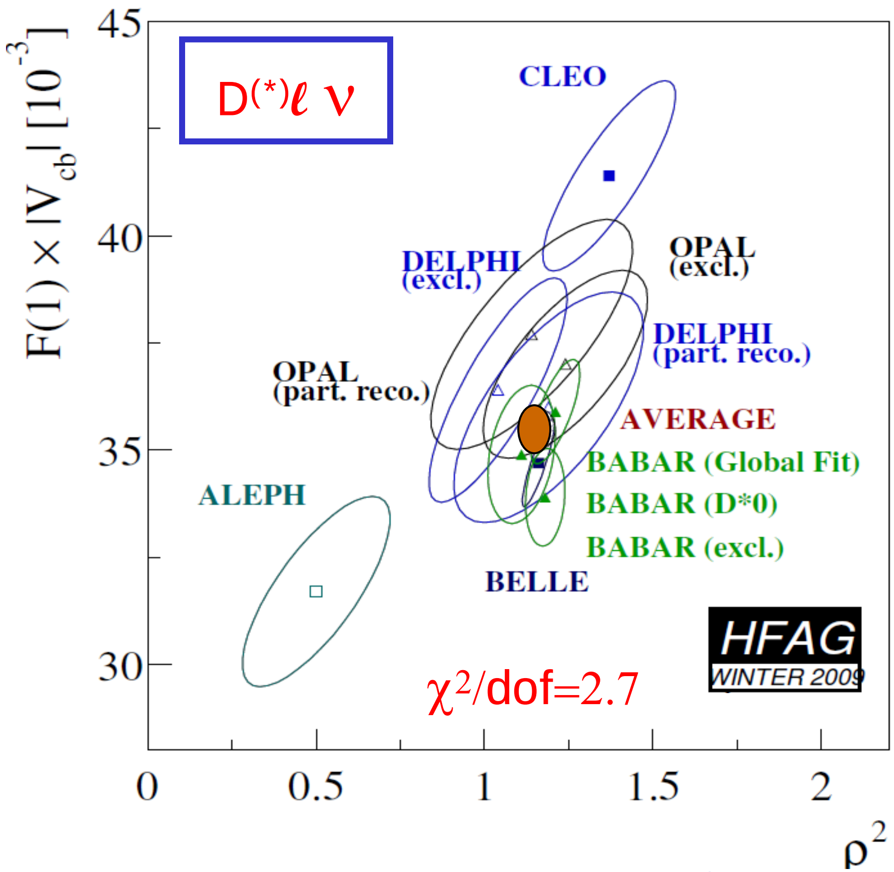
- BABAR: 3,255±82 fully reconstructed

  Reduces combinatorial Background
- Fit absolute to $d\Gamma/dw$ distributions to extract $|V_{cb}|$ G(1) and ρ^2
- Reduction is uncertainties by factor of 5!



$|V_{cb}|$ Measurements based on $B \to D^{(*)} \ell^+ \nu$ Decays





$\eta G(1)|V_{cb}| = (42.3 \pm 0.7_{stat} \pm 1.3_{syst})\ 10^{-3}$

$\eta\ G(1) = 1.082 \pm 0.024$ Okamoto, FNAL 2004

$|V_{cb}| = (39.1 \pm 1.4_{exp} \pm 0.87_{theo})\ 10^{-3}$

3.5% 2.2%

$\eta F(1)|V_{cb}| = (35.75 \pm 0.42)\ 10^{-3}$

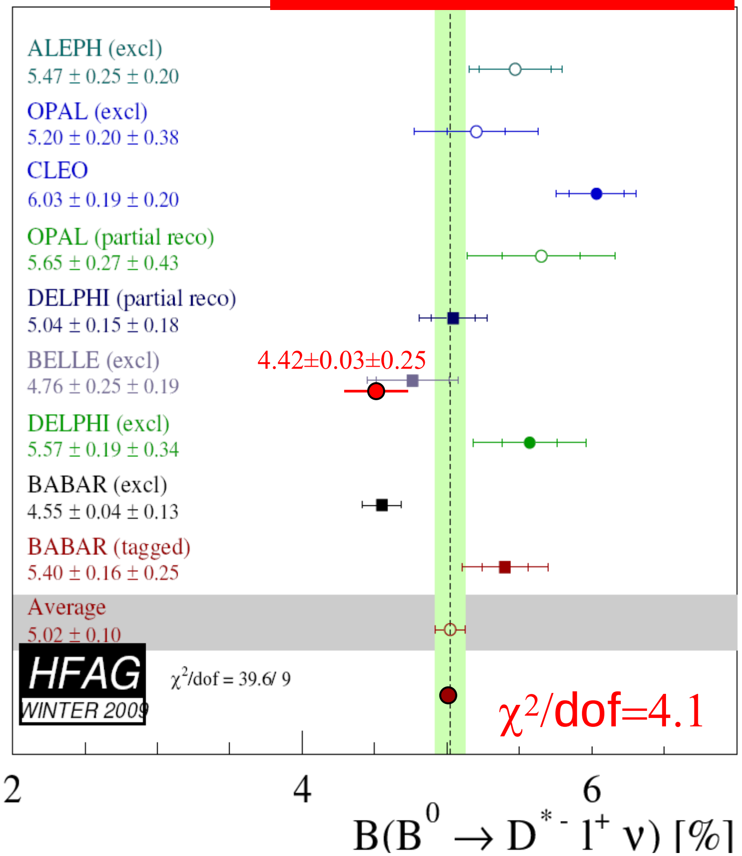
$\eta\ F(1) = 0.927 \pm 0.024$ (FNAL/MILC, PRD 2009)

$|V_{cb}| = (38.6 \pm 0.45_{exp} \pm 1.00_{theo})\ 10^{-3}$

1.2% ?? 2.6%

Dilemma: $B \to X_c \ell \nu$ Exclusive BF Measurements !!

Exclusive: $D^* \ell \nu$



Exp. errors are underestimated!

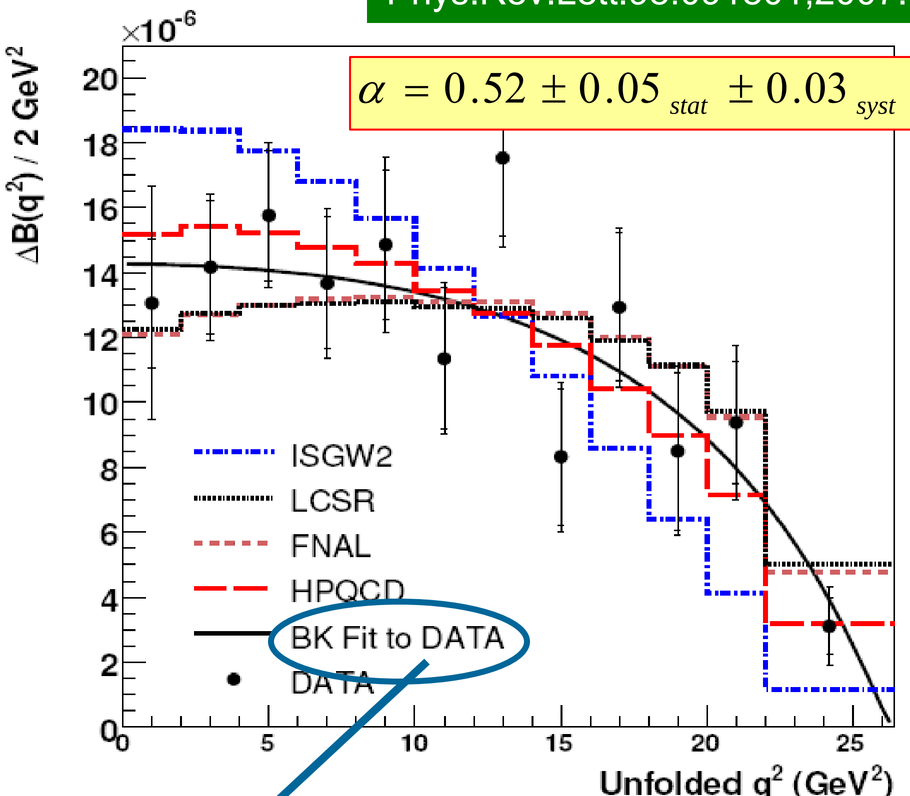
- Sum of exclusive BF does not add up to total $X_c l\nu$ – 1.4% unaccounted

Decay	BF (%)
$Dl\nu$	2.2 ± 0.1
$D^*l\nu$	4.9 ± 0.4 *
$D^{**}l\nu$	1.6 ± 0.2 **
Sum B0	8.7 ± 0.4
$X_c l\nu$	10.1 ± 0.3

- Poor agreement for $D^*l\nu$ BF
- Unknown partial BF of D** states
- Missing decay modes? Extra π, η
- This impacts many measurements!
- An embarrassment, but unlikely to be resolved soon!

Exclusive $|V_{ub}|$ measurements: $B \to \pi \ell \nu$ BK Ansatz

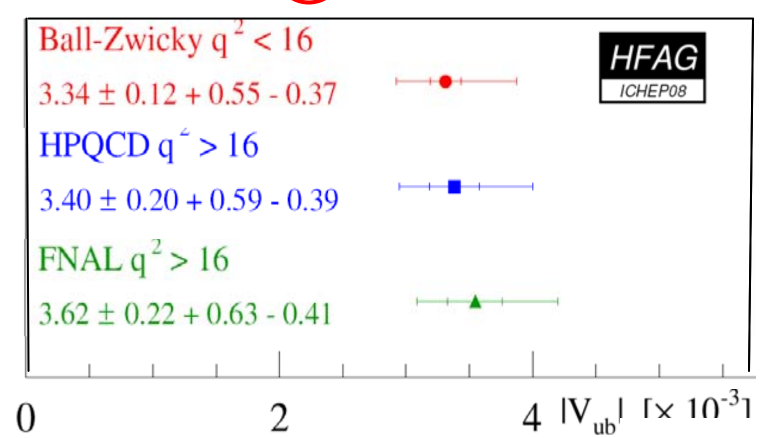
BABAR: 230 M BB Events
Phys.Rev.Lett.98:091801,2007.



Becirevic-Kaidalov parameterization

$$f_+(q^2) = \frac{1}{(1 - q^2/m_{B^*}^2)(1 - \alpha q^2/m_{B^*}^2)}$$

- $$\frac{d\Gamma}{dq^2}(B \to \pi l \nu) = \frac{G_F^2}{24\pi^3} p_\pi^3 \, |V_{ub}|^2 |f_+(q^2)|^2$$
- Combine measured partial BF with $f_+(q^2)$ predicted by QCD, in restricted q^2 regions
- Requires analytic parameterization of $f_+(q^2)$ and $f_0(q^2)$ – commonly use BK, parameter α
- $$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(q^2_{min}, q^2_{max})}{\tau_0 \, \Delta\zeta(q^2_{min}, q^2_{max})}}$$



$$|V_{ub}| = (3.40 \pm 0.20^{+0.59}_{-0.39}) \cdot 10^{-3}$$

6% 11-17%

Exclusive $|V_{ub}|$ measurements: $B\to\pi\ell\nu$ BGL Ansatz

Boyd, Grinstein, Lebed (1995)
Becher, Hill (2006)

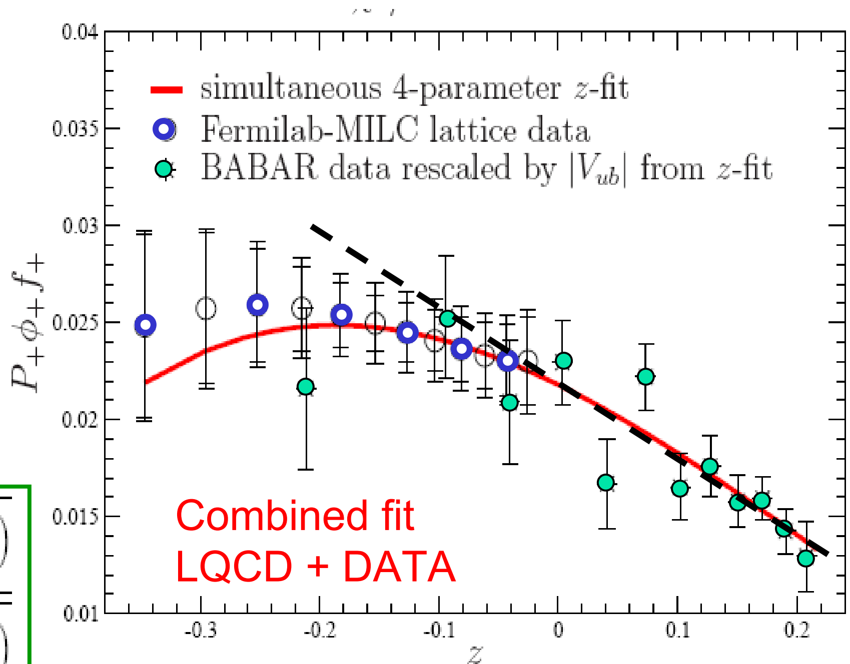
BABAR: 230 M BB Events
Phys.Rev.Lett.98:091801,2007.

- BK Parameterization simple, but introduces unknown uncertainties
- Based on dispersion relations and analyticity BGL introduced expansion in new variable z

$$P(q^2)\Phi f_+(q^2) = \sum_k a_k z(q^2)^k$$

Accounts for sub-threshold poles

$$z(q^2, q_0^2) = \frac{\sqrt{m_+^2 - q^2)} - \sqrt{m_+^2 - q_0^2)}}{\sqrt{m_+^2 - q^2)} + \sqrt{m_+^2 - q_0^2)}}$$



$$
\begin{aligned}
|V_{ub}| \times 10^3 &= 3.38 \pm 0.36 \quad 11\% \\
a_0 &= 0.0218 \pm 0.0021 \\
a_1 &= -0.0301 \pm 0.0063 \\
a_2 &= -0.059 \pm 0.032
\end{aligned}
$$

- Thus only few parameters to describe the FF. Need FF normalization
- Current data fit linear or quadratic ansatz !

New BABAR Analysis in preparation

Summary on $|V_{cb}|$ and $|V_{ub}|$

Inclusive Decays:

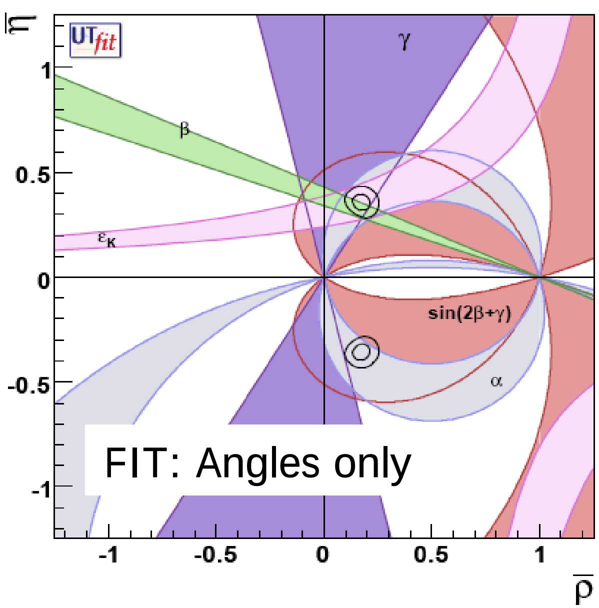
$|V_{ub}| = 4.06 \cdot 10^{-3}\ (1.00 \pm 0.04_{exp} \pm 0.07_{thy})$ $|V_{cb}| = 41.5 \cdot 10^{-3}\ (1.00 \pm 0.012_{fit} \pm 0.015_{thy})$

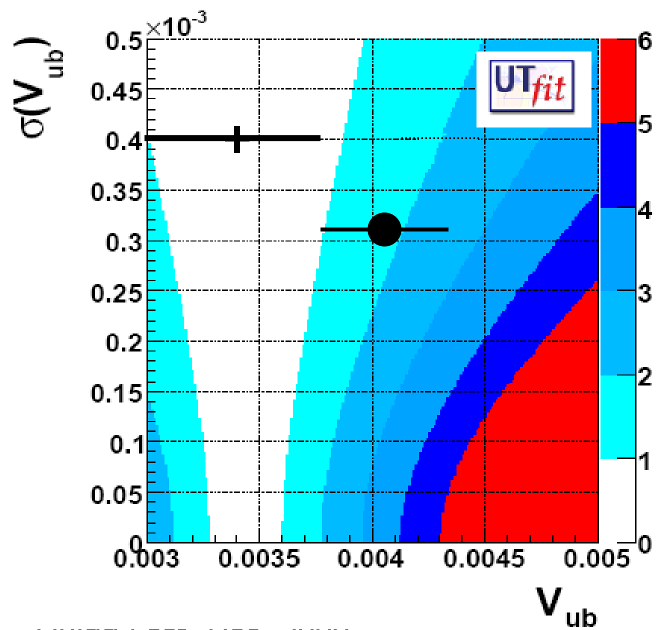
Exclusive Decays:

$|V_{ub}| = 3.38 \cdot 10^{-3}\ (1.00 \pm 0.03_{exp} \pm 0.09_{thy})$ $|V_{cb}| = 38.6 \cdot 10^{-3}\ (1.00 \pm 0.016_{exp} \pm 0.023_{thy})$

GLOBAL FIT of CKM Parameters – UT Fit

$|V_{ub}|_{Pred} = 3.50 \cdot 10^{-3}\ (1.00 \pm 0.04)$ $|V_{cb}|_{pred} = 41.17 \cdot 10^{-3}\ (1.00 \pm 0.021)$





● $B \to \pi l \nu$ BABAR BGL fit

+ Incl. $B \to X_u l \nu$ HFAG (BNLP)

Best Wishes for Many Years of Fascinating Research